Cracking and Durability in Sustainable Concretes

Sponsored by
ACI Committees 130, Sustainability of Concrete
and 224, Cracking

The Concrete Convention and Exposition
October 15-19, 2017
Anaheim, California, USA

Editors:
Ralf Leistikow and
Kimberly Waggle Kramer

American Concrete Institute
Always advancing

SP-336

SP-336-7

Low-Cracking High-Performance Concrete (LC-HPC) for Durable Bridge Decks

David Darwin, Rouzbeh Khajehdehi, Muzai Feng,
James Lafikes, Eman Ibrahim, Matthew O'Reilly

Synopsis: The goal of this study was to implement cost-effective techniques for improving bridge deck service life through the reduction of cracking. Work was performed both in the laboratory and in the field, resulting in the creation of Low-Cracking High-Performance Concrete (LC-HPC) specifications that minimize cracking through the use of low slump, low paste content, moderate compressive strength, concrete temperature control, good consolidation, minimum finishing, and extended curing. This paper documents the performance of 17 decks constructed with LC-HPC specifications and 13 matching control bridge decks based on crack surveys. The LC-HPC bridge decks exhibit less cracking than the matching control decks in the vast majority of cases. Only two LC-HPC bridge decks have higher overall crack densities than their control decks, which are the two best performing control decks in the program, and the differences are small. The majority of the cracks are transverse and run parallel to the top layer of the deck reinforcement. The results of this study demonstrate the positive effects of reduced cement paste contents, concrete temperature control, limitations on or de-emphasis of maximum concrete compressive strength, limitations on maximum slump, the use of good consolidation, minimizing finishing operations, and application of curing shortly after finishing and for an extended time on minimizing cracking in bridge decks.

Keywords: bridge decks, consolidation, cracking, curing, finishing, high-performance concrete, temperature control

INTRODUCTION

Deterioration of bridges is a widespread and costly sustainability problem faced by society. In 2016, 9.1% of bridges in the U.S. were rated as structurally deficient (ASCE 2017). An average of 188 million trips were made over these deficient bridges daily. Cracking of concrete bridge decks is one major factor that causes bridges to become deficient. Cracks allow chlorides and moisture to reach the reinforcing steel in the bridge decks, resulting in corrosion. This in turn can lead to spalling of the concrete and a reduction in the service life of the bridge (Lindquist et al. 2005, Lindquist et al. 2006). Moreover, bridge deck cracking increases the vulnerability of concrete to freeze-thaw damage, further compromising the sustainability of bridge structures.

In response to these crack-related problems, a 13-year, two-phase pooled-fund program at the University of Kansas, titled *Construction of Crack-Free Bridge Decks,* was developed with the goal of implementing the most cost-effective techniques to reduce cracking construct more durable bridge decks. To accomplish this goal, the researchers completed the following tasks:

1. Developed a detailed plan to construct bridge decks with minimum cracking by incorporating "best practices" dealing with materials, construction procedures, and structural design. These practices were developed into Low-Cracking, High Performance Concrete (LC-HPC) specifications for high-quality sustainable concrete bridge decks.
2. Worked with state DOTs, designers, contractors, inspectors, and material suppliers to modify designs, specifications, contracting procedures, construction techniques, and materials to obtain decks exhibiting minimal cracking.
3. Selected and scheduled bridges to be constructed using LC-HPC specifications, and pre-qualify designers and contractors in application of the techniques.
4. Performed detailed crack surveys on bridge decks built following LC-HPC specifications as well as decks built following conventional practices.
5. Correlated the cracking measured in Task 4 with environmental and site conditions, construction techniques, design specifications, and material properties, and compared results with earlier data.
6. Documented the results of the study. Those results have been documented during the 13-year term of the study through a series of reports and papers describing the development of crack reduction technologies and the performance of the bridges constructed in the program. These are listed in a bibliography provided by Darwin et al. (2016).

The LC-HPC specifications involved concrete mixtures with low cement paste contents, low slump, and moderate rather than high strength. Improved construction procedures, including concrete temperature control, minimum finishing, and an early start coupled with extended curing, were also followed. The result was a reduction in plastic shrinkage, settlement, thermal, and drying shrinkage cracking, all of which contribute to cracking in bridge decks and compromise the sustainability of bridge structures.

The study involved cooperation between state departments of transportation, cement companies and other material suppliers, contractors, and designers. Work was performed both in the laboratory and in the field, resulting in the construction of 17 bridge decks (in 22 placements) in Kansas that were let under LC-HPC specifications. The study was performed in two phases, concluding in 2016. In addition, two bridge decks were constructed in Minnesota under LC-HPC specifications, along with control decks, the performance of which was reported by Pendergrass et al. (2013).

In 2005, the Kansas Department of Transportation (KDOT) with participation of the University of Kansas as part of this study started constructing bridge decks following LC-HPC specifications covering aggregate, concrete, and construction practices. Thirteen of these decks were paired by KDOT with control decks that had similar structural design, traffic volume, age, and environmental exposure conditions.

Seventeen LC-HPC bridges were planned for construction. The specifications were not followed for one of the bridge decks; all 17, however, remained in the study. Bridges that were constructed in accordance with the LC-HPC specifications are labeled as LC-HPC-1 through 13, 15, 16, and 17. The single bridge that was not constructed in accordance with LC-HPC specifications is labeled as OP-14 (Overland Park 14) and is the only one of the 17 bridges not constructed under the supervision of the Kansas Department of Transportation. Control bridges are labeled Control-1/2, 3 through 7, 8/10, 9, 11, 12, and 13. LC-HPC-1 and LC-HPC-2 were paired to the same control deck, designated as Control-1/2; and LC-HPC-8 and LC-HPC-10 were paired to one control deck, designated as Control-8/10. The bridge numbers reflect the order in which the bridges were let, not the order in which they were constructed. Most of the bridge decks in this study are supported by steel girders. LC-HPC-8, LC-HPC-10, and Control-8/10, however, are supported by precast-prestressed concrete girders.

Every year, crack surveys were performed to compare the cracking performance of the LC-HPC decks with that of the control decks. In this paper, crack survey data for years 2014 through 2017 are summarized. Four prior reports have been published with the specific goal of summarizing the crack survey results for 2006 through 2015. Gruman, Darwin, and Browning (2009) summarized the crack survey results for 2006, 2007, and 2008. Pendergrass, Darwin, and Browning (2011) summarized the crack survey results for 2009 and 2010. Kaul, Darwin and Browning (2012) and Bohaty, Riedel, and Darwin (2013) summarized the crack survey results for 2011, 2012 and 2013, and Alhmood, Darwin, and O'Reilly (2015) summarized the crack survey results for 2014 and 2015. This paper extends the work of Alhmood et al. (2015) to include the last surveys performed in 2016 and 2017. Full details are presented by Darwin et al (2016). In addition to the summaries of the crack survey results, four in-depth reports by Lindquist, Darwin, and Browning (2008), McLeod, Darwin, and Browning (2009), Yuan, Darwin, and Browning (2011), and Pendergrass and Darwin (2014) have been issued that address the evaluation of crack reduction technologies for both effectiveness and their impact on the durability of the resulting concrete (some of the findings are being implemented in follow-on studies and by programs outside of this pooled-fund study), the key parameters that control cracking in bridge decks, and the experiences involved in the construction of the LC-HPC decks, the performance of the bridge decks constructed under this program, and the lessons learned from the construction and evaluation of those decks.

RESEARCH SIGNIFICANCE

The studies described in this paper have had a major impact on the construction of bridge decks in the U.S. Many of the recommendations have been adopted by departments of transportation in multiple states within their regular bridge deck specifications, including reduced cementitious material and cement paste contents, improved early-age and long-term curing, limitations on or de-emphasis of maximum concrete compressive strength, limitations on maximum slump, and minimizing finishing operations. The result has been a significant reduction in cracking and improvement in durability of concrete bridge decks.

SPECIFICATIONS

Three special provisions of the Kansas Department of Transportation (KDOT) standard specifications have been developed for LC-HPC bridge decks. These special provisions cover the requirements for aggregate, concrete, and construction practices with the goal of reducing cracking of concrete bridge decks (Kansas Department of Transportation 2007a, b, c). The latest versions of the special provisions are presented by Darwin et al. (2016). The special provisions are written to minimize the potential for plastic shrinkage and settlement cracking in plastic concrete and drying shrinkage and thermal cracking in hardened concrete. The background for the approach taken to achieve these goals is presented by Schmitt and Darwin (1995, 1999), Darwin et al. (2004, 2010, 2012), Lindquist et al. (2005), Browning et al. (2007, 2009), and Darwin (2014). The requirements of the LC-HPC specifications are summarized below.

Aggregate

The coarse aggregate must be gravel, chat, or crushed stone. The minimum soundness and the maximum absorption should be 0.9 and 0.7, respectively. Table 1 lists the maximum allowable percentages of deleterious substances.

The fine aggregate must be natural sand (Type FA-A) or chat (Type FA-B). Moreover, these aggregate types must meet both the KDOT and the AASHTO requirements for mortar strength and organic impurities, respectively. Table 2 and Table 3 show the provisions on deleterious substances for natural sand and chat, respectively.

The combined aggregate gradation must be obtained by implementing a proven optimization method such as the KU Mix (Lindquist et al. 2008, 2015) or Shilstone (1990) Methods.

Table 1—Deleterious substance requirements for coarse aggregate

Substance	Maximum % Allowable by Weight
Material passing No. 200 sieve	2.5%
Shale or shale-like material	0.5%
Clay lumps and friable particles	1.0%
Sticks (including absorbed water)	0.1%
Coal	0.5%

Table 2—Deleterious substance requirements for type FA-A (Natural Sand)

Substance	Maximum % Allowable by Weight
Material passing No. 200 sieve	2.0%
Shale or shale-like material	0.5%
Clay lumps and friable particles	1.0%
Sticks (including absorbed water)	0.1%

Table 3—Deleterious substance requirements for type FA-B (Chat)

Substance	Maximum % Allowable by Weight
Material passing No. 200 sieve	2.0%
Clay lumps and friable particles	0.25%

Concrete

The cement content must be between 500 and 540 lb/yd^3 (297 and 320 kg/m^3). The water-cement ratio (by weight) must be between 0.44 and 0.45. The combined requirements for cement content and water-cement ratio ensure that the cement paste content will be below 26 percent by volume. The engineer in charge may approve a reduction in the water-cement ratio to 0.43 at the bridge construction site. All of the LC-HPC bridge decks discussed in this report, with the exception of LC-HPC 15 and 16, were constructed using 535 or 540 lb/yd^3 of concrete (317 and 320 kg/m^3). Bridge decks for LC-HPC 15 and 16 contained concrete with cement contents of 500 lb/yd^3 (297 kg/m^3) and 520 - 540 lb/yd^3 (308 to 320 kg/m^3), respectively. Table 4 and Table 5 list the concrete mix proportions for LC-HPC and control bridges, respectively.

Concrete must be sampled at the discharge of the pump, conveyor, or bucket. The allowable air content (by volume) ranges from 6.5 to 9.5%. To limit settlement cracking over the reinforcing bars, current specifications state that the concrete slump should range from 1½ to 3 in. (38 to 76 mm); the maximum allowable slump at the truck is 3½ in. (90 mm). When LC-HPC 1 through 13 were constructed, the specifications had a maximum limit on slump of 4 in. (100 mm). The concrete temperature at the time of placement should not exceed 70°F (21°C) and should not be lower than 55°F (13°C). The construction engineer in charge may permit the temperature to be 5°F (3°C) outside of this range. After the construction of LC-HPC 1 through 13, the LC-HPC specifications were modified to set a lower and upper limit for the compressive strength of concrete, with a 28-day compressive strength between 3500 and 5500 psi (24.1 and 37.0 MPa).

The use of vinsol resin or tall oil-based air-entraining admixtures is permitted per the LC-HPC specifications. The use of mineral, set-accelerating, or set-retarding admixtures is prohibited. The current specification allows for a Type A water-reducer or dual-rated Type A-F water-reducer. A Type F high-range water-reducer can be used if concrete complies with the plastic and hardened concrete properties specifications. If slump on site needs to be adjusted, it can be done only by adding water-reducing or high-range water-reducing admixtures. Withholding any portion of water during batching is not allowed.

Construction

Ambient temperature, wind speed, relative humidity 12 in. (30 cm) above the deck, and the plastic temperature of concrete must be measured at least once per hour by KDOT personnel. At all times during the construction process, the evaporation rate must remain under 0.2 lb/ft^2/hr (1 kg/m^2/hr). If the evaporation rate upper limit is exceeded, concrete cooling, wind break installation, or other procedures must be implemented to reduce the evaporation rate; fogging the concrete, however, is prohibited.

LC-HPC specifications allow contractors to use buckets, conveyors, or pumps to place concrete. A concrete pump may only be used if the contractor has demonstrated the ability to pump the LC-HPC concrete during the construction of the qualification slab. To avoid loss of entrained air in concrete, it is not acceptable to drop concrete from a height greater than 5 ft (1.5 m), and concrete pumps must have an air cuff or bladder valve to limit the free fall of concrete that may cause a loss in air. The concrete must be consolidated using vertically-mounted internal gang vibrators placed on 1-ft (305 mm) centers across the bridge deck. Saturated burlap must be placed on the finished concrete within 10 minutes of finishing, and the decks must be wet-cured for 14 days using soaker hoses under plastic. Curing is followed by application of curing compound for seven days to slow the rate of evaporation, which allows the concrete more time for creep to relieve tensile stresses due to early-age drying shrinkage.

The concrete supplier and contractor must demonstrate the ability to meet all the specifications by preparing both a qualification batch and a qualification concrete slab using LC-HPC concrete before the bridge deck is constructed (Kansas Department of Transportation 2007c). Before the qualification batch is verified, the actual jobsite haul time must be simulated. All admixtures must be included in the qualification batch. The same personnel and equipment must be used to place both the qualification slab and the LC-HPC bridge deck. If the concrete meets the LC-HPC specifications during the construction of the qualification slab, those mixture proportions may be used for the bridge deck.

Table 4—Mix design properties for LC-HPC bridges

Bridge	Cement	Water	*w/c*	Fine Aggregate		Coarse Aggregate — Max Size Agg.			Paste Content
				#1	#2	3/4 in. (CA-5)	1-1/2 in. (CA-6)	3/8 in. (CA-7)	
	(lb/yd^3)	(lb/yd^3)		(lb/yd^3)		(lb/yd^3)			(% by volume)
LC-HPC-1 p1	540	243	0.45	1246*	-	565	890	266	24.6
LC-HPC-1 p2									
LC-HPC-2									
LC-HPC-3	535	241	0.45	1071*	387[†]	862	654	-	24.4
LC-HPC-4 p1	535	225	0.42	526*	1001[†]	774	723	-	23.4
LC-HPC-4 p2	535	225	0.42	1089*	393[†]	877	665	-	23.4
LC-HPC-5	535	225	0.42	1089*	393[†]	877	665	-	23.4
LC-HPC-6	535	241	0.45	1071*	387[†]	862	654	-	24.4
LC-HPC-7	540	243	0.45	1407**	-	599	988	-	24.6
LC-HPC-8	535	223	0.42	465*	1122[$]	745	707	-	23.4
LC-HPC-9[‡]	535	235	0.44	1419[$]	-	1189	373	-	24.1
LC-HPC-10	535	223	0.42	465*	1122[$]	745	707	-	23.4
LC-HPC-11	535	225	0.42	1467[##]	-	312[††]	312	1030	23.4
LC-HPC-12 p1	540	238	0.44	1438**	-	360	1199	-	24.3
LC-HPC-12 p2	535	239	0.45	1415**	-	855	805	-	24.2
LC-HPC-13	535	235	0.44	415*	1059[$]	-	1510	-	24.1
OP p1	535	241	0.45	974**	392[†]	875	745	-	24.4
OP p2									
OP p3									
LC-HPC-15	500	225	0.45	1472[##]	-	1166	429[‡‡]	-	22.8
LC-HPC-16[#]	500	225	0.45	1472[##]	-	1166	429[‡‡]	-	22.8
LC-HPC-17	540	243	0.45	1470[##]	220[$$]	789	497[‡‡]	-	24.6

‡ Cement content increased to 540 lb/yd^3 for deck placement; [#] Cement content was increased to 520 and 540 lb/yd^3 for deck placement; *Designated as FA-A; ** Designated as MA-2 in KDOT Specs; [##] Designated as MA-3 in KDOT Specs; [†] Manufactured sand; [††] Designated as CA-1 in KDOT Specs; [‡‡] Designated as MA-4 in KDOT Specs; [$] Designated at BD-2 in KDOT Specs; [$$] Pea Gravel.

Note: 1 lb/yd^3 = 0.5933 kg/m^3, 1 in. = 25 mm

Table 5—Mix design properties for Control bridges

Bridge	Deck Section	Cement	Class F Fly Ash	Silica Fume	Water	*w/c*	Fine Aggregate (FA-A)	Coarse Aggregate CA-5	Coarse Aggregate CA-7	Paste Content
		(lb/yd^3)	(lb/yd^3)	(lb/yd^3)	(lb/yd^3)		(lb/yd^3)	(lb/yd^3)		(% by volume)
Control 1/2 p1	Subdeck	602	-	-	241	0.40	1493	1493	-	25.6
	Overlay	583	-	44	233	0.37	1488	-	1488	26.0
Control 1/2 p2	Subdeck	605	-	-	241	0.40	1493	1493	-	25.7
	Overlay	583	-	44	233	0.37	1488	-	1488	26.0
Control 3	Subdeck	536	133	-	268	0.40	Not Available			29.0
	Overlay	583	-	44	233	0.37	Not Available			26.0
Control 4	Subdeck	536	133	-	268	0.40	Not Available			29.0
	Overlay	583	-	44	233	0.37	Not Available			26.0
Control 5	Subdeck	536	133	-	268	0.40	Not Available			29.0
	Overlay	583	-	44	233	0.37	Not Available			26.0
Control 6	Subdeck	536	133	-	268	0.40	Not Available			29.0
	Overlay	583	-	44	233	0.37	Not Available			26.0
Control 7 p1	Subdeck	536	133	-	268	0.40	1419	1419	-	29.0
	Overlay	583	-	44	233	0.37	1488	-	1488	26.0
Control 7 p2	Subdeck	536	133	-	268	0.40	1419	1419	-	29.0
	Overlay	583	-	44	233	0.37	1488	-	1488	26.0
Control 8/10	Monolithic	612	-	-	244	0.40	Not Available			26.0
Control 9	Subdeck	612	-	-	244	0.40	1478	1478	-	26.0
	West Overlay / East Overlay	590	-	44	234	0.37	1485	-	1485	26.2
Control 11	North Subdeck	602	-	-	241	0.40	1508	1478	-	25.6
	South Subdeck	602	-	-	241	0.40	1508	1478	-	25.6
	Overlay	583	-	44	233	0.37	1490	-	1490	26.0
Control 12 p1	Subdeck	602	-	-	265	0.44	1455	1455	-	27.1
	Overlay	581	-	44	231	0.37	1475	-	1475	25.8
Control 12 p2	Subdeck	602	-	-	265	0.44	1455	1455	-	27.1
	Overlay	581	-	44	231	0.37	1475	-	1475	25.8
Control 13	Subdeck	612	-	-	244	0.40	1478	1478	-	26.0
	Overlay	590	-	44	234	0.37	1485	-	1485	26.2

Note: 1 lb/yd^3 = 0.5933 kg/m^3, 1 in. = 25 mm

CRACK SURVEY PROCEDURE

Crack surveys for both LC-HPC and control bridge decks are performed annually. The surveys are performed in accordance with the specifications presented by Darwin et al. (2016) and are summarized next.

Procedure

To provide accurate and comparable results, a standard procedure is followed for crack surveys. Crack surveys must be performed only on a day that is at least mostly sunny. The air temperature should not be less than 60°F (16°C) at the time of surveying. Moreover, the bridge deck should be completely dry. The crack survey is invalid if it rains during the time of the survey or if the sky becomes overcast.

A scaled plan (map) for the bridge deck is developed and printed before the survey. These plans serve as the template to indicate the location and length of the cracks on the bridge deck, and they should include a compass indicating north. Plans should be developed at a scale of 1 in. = 10 ft (25.4 mm = 3.048 m). Furthermore, a 5 ft × 5 ft (1.524 m × 1.524 m) grid should be printed on a separate paper and placed underneath the deck plan; this grid should match the bridge grid that is placed on the deck. The grid helps the surveyors keep track of crack location and length. Some human error is involved when drawing the cracks.

Traffic control is provided to ensure the safety of the surveyors during the bridge survey. After closing at least one lane of the bridge to traffic, two surveyors draw a 5 ft × 5 ft (1.524 m × 1.524 m) grid on the bridge deck using chalk or lumber crayons. This grid is called the bridge grid and should match the grid drawn on the plans. Surveyors mark any cracks they can see while bending at waist height. Surveyors should not mark any crack that cannot be seen from waist height. When surveyors see a crack, they may bend closer and trace the crack to its end, including portions of the same crack that cannot be seen from waist height. If the surveyors see another crack while tracing a crack (not attached to the crack being traced), they do not mark it unless it can also be seen when bending from waist height. After marking a crack, the surveyors return to the location where they started marking the crack and continue surveying. At least two surveyors inspect each section of the bridge. This method results in consistent crack survey results between surveys (Lindquist et al. 2005, 2008). After cracks are marked on the bridge, another surveyor draws the marked cracks on the scaled bridge plan.

In addition to marking cracks, a standard crack comparator is used for measuring the width of the cracks. In case of a low cracking deck, all crack widths are measured. When the crack density is high, a representative number of cracks over the deck is selected for crack width measurements.

To determine crack density, the bridge plans with the marked cracks are scanned into a computer and converted to AutoCAD files. In AutoCAD, any lines on the bridge plan not representing cracks (such as bridge abutments or boundaries) are erased. The total length of the cracks can then be measured using AutoCAD. Crack density is calculated by dividing the total length of the cracks by the area of the bridge deck. Crack densities are reported in m/m^2 for the whole bridge, each placement, and each span.

RESULTS

The type of results obtained in the bridge deck cracking surveys can be illustrated by LC-HPC 4 and Control-4. LC-HPC-4 is the first unit of the southbound US-69 ramp to I-35 over 103rd Street in Overland Park, Kansas (Kansas City metro area), and Control-4 is the Antioch Road to westbound I-435 ramp that spans over the 103rd Street to US-69 south ramp, also in Overland Park. The deck on LC-HPC-4 was constructed in two placements. Placement 1 was cast on September 29, 2007 and Placement 2 was cast on October 2, 2007. The bridge deck for Control-4 was constructed on August 5, 2007. Both decks have been surveyed 8 times, with the most recent surveys in 2015.

Figures 1 and 2 show, respectively, the crack maps for LC-HPC-4 and Spans 1 and 2 of Control-4. As can be seen in the figures, the majority of cracks present are transverse, although longitudinal cracks do form, especially adjacent to abutments. As observed on most bridges decks in the study, both decks exhibit cracking within the positive and as well as the negative moment regions. The average crack density for LC-HPC-4 shown in Fig. 1 is 0.217 m/m^2. The density for Spans 1 and 2 of Control-4 shown in Fig. 2 are 0.458 and 0.774 m/m^2, respectively. For all of Control-4, the average crack density is 0.755. Figure 3 compares crack densities of LC-HPC 4 and Control-4 over time. As shown in the figure, both LC-HPC-4 placements have exhibited much less cracking than Control-4.

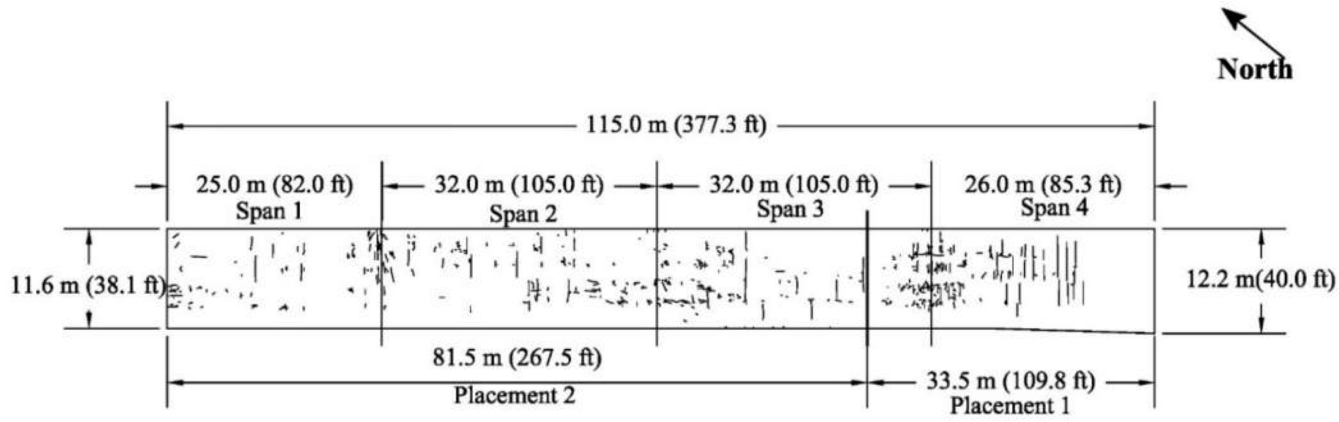

Fig. 1—2015 crack map of LC-HPC-4

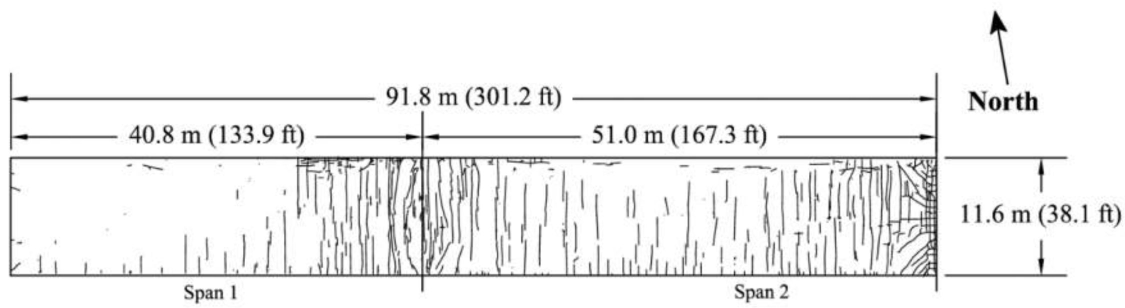

Fig. 2—2015 crack map of Spans 1 and 2 of Control-4

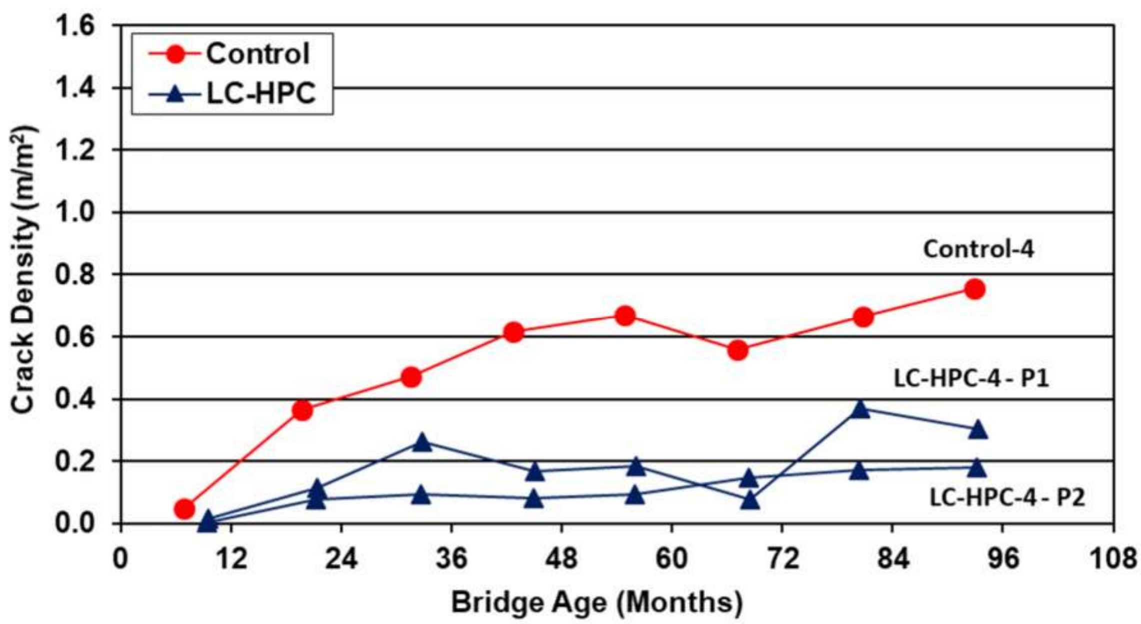

Fig. 3— Crack Densities versus Deck Age for LC-HPC-4 and Control-4

Tables A.1 and A.2 in Appendix A summarize the crack densities for the bridge decks surveyed in 2014 and 2015, respectively. Table A.3 summarizes the crack densities for the bridge decks surveyed in 2016 and 2017. Due to high amounts of cracking, surveys on Control-5 ended in 2011 and surveys on Control-7, LC-HPC-12, and Control-12 ended in 2014. The crack densities obtained in the final surveys are included in the tables. Four decks were surveyed in 2016 (LC-HPC-3, Control-3, LC-HPC-11, and Control-11) and three decks in 2017 (LC-HPC-15, LC-HPC-16, and LC-HPC-17) to obtain final data for those projects (Table A.3). The crack maps for the 2014, 2015, and 2016 surveys are reported by Darwin et al. (2016). The results of the surveys performed in 2006, 2007, and 2008 were reported by Gruman, Darwin, and Browning (2009), those performed in 2009 and 2010 were reported by Pendergrass, Darwin, and Browning (2011), and those performed in 2011, 2012, and 2013 were reported by Kaul, Darwin and Browning (2012) and Bohaty, Riedel, and Darwin (2013).

The highest recorded crack density on an LC-HPC deck was 0.66 m/m^2 (LC-HPC-3 at 79.3 months) and the highest crack density on a control deck was 1.165 m/m^2 (Placement 1 of Control-7 at 98.5 months). Bridge deck OP-14 was not constructed in accordance with LC-HPC specifications; high slump concrete was used, the concrete was not properly consolidated, and the deck was over-finished, delaying curing. As a result, OP-14 has exhibited excessive cracking throughout its life. Two of the three placements of OP-14 exhibit the highest crack densities among all decks included in this study (1.331 m/m^2 for Placement 2 and 1.387 m/m^2 for Placement 3).

Figure 4 shows crack density versus time for the bridge decks included in this study, including OP-14. The south lane of LC-HPC-11 and decks LC-HPC-12 and Control-12 have been excluded. The south lane of LC-HPC-11 experiences a high amount of heavy truck traffic and, as a result, exhibits structural cracking. LC-HPC-12 and Control-12 were subjected to unusual torsional loading during construction that has affected the cracking performance of both decks. Although, the south lane of LC-HPC-11 and LC-HPC-12 have been excluded, both LC-HPC 11 (before excluding the south lane) and LC-HPC-12 have lower cracking than their control pairs. As shown in Fig. 4, the LC-HPC decks have exhibited lower overall cracking than the control decks. There is, however, some overlap, with some of the LC-HPC decks exhibiting higher crack densities than some of the control decks because they were constructed by different contractors (Yuan et al. 2011, Pendergrass and Darwin 2014) and have experienced different conditions.

Figure 5 shows that when the crack density of each LC-HPC deck (if a bridge had more than one placement, the average crack density of the placements are used) is compared with its corresponding control deck, LC-HPC decks have performed better than their control pairs in 10 of 12 cases. The two control decks (Control 1/2 and Control 3) that are performing better than their paired LC-HPC decks are the two best performing control decks in the program, and the differences in crack density between the LC-HPC and control deck is each case is small. As shown in Fig. 5, both LC-HPC decks supported by precast-prestressed girders (LC-HPC-8 and LC-HPC-10) performed better than the control deck (Control-8/10).

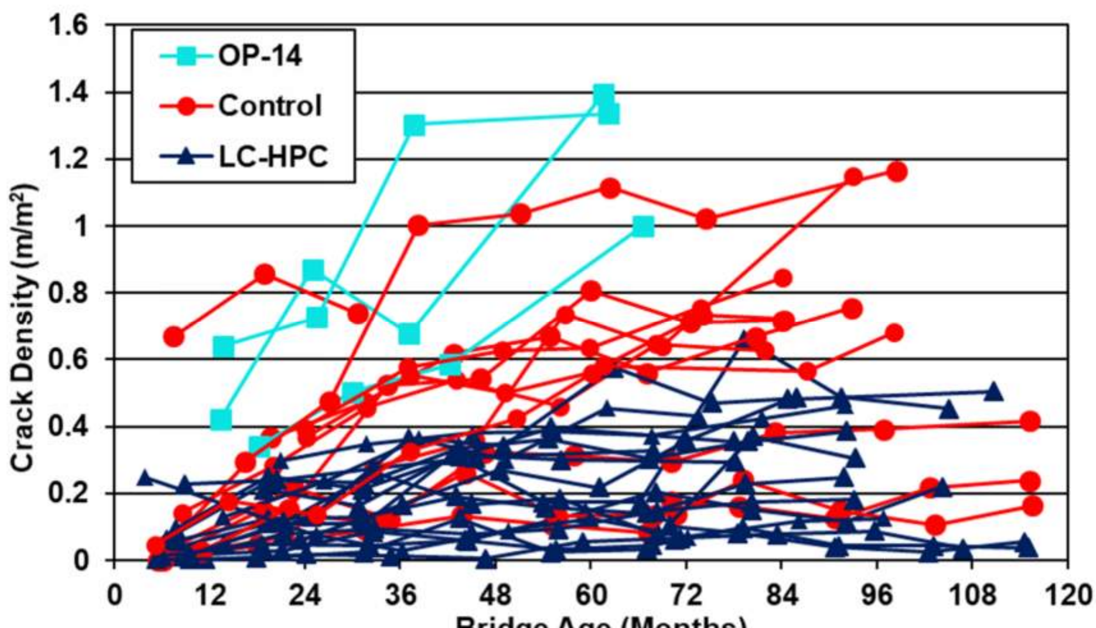

Fig. 4— LC-HPC and Control decks crack densities versus deck age*
**LC-HPC-12, Control-12, and south lane of LC-HPC-11 are not shown*

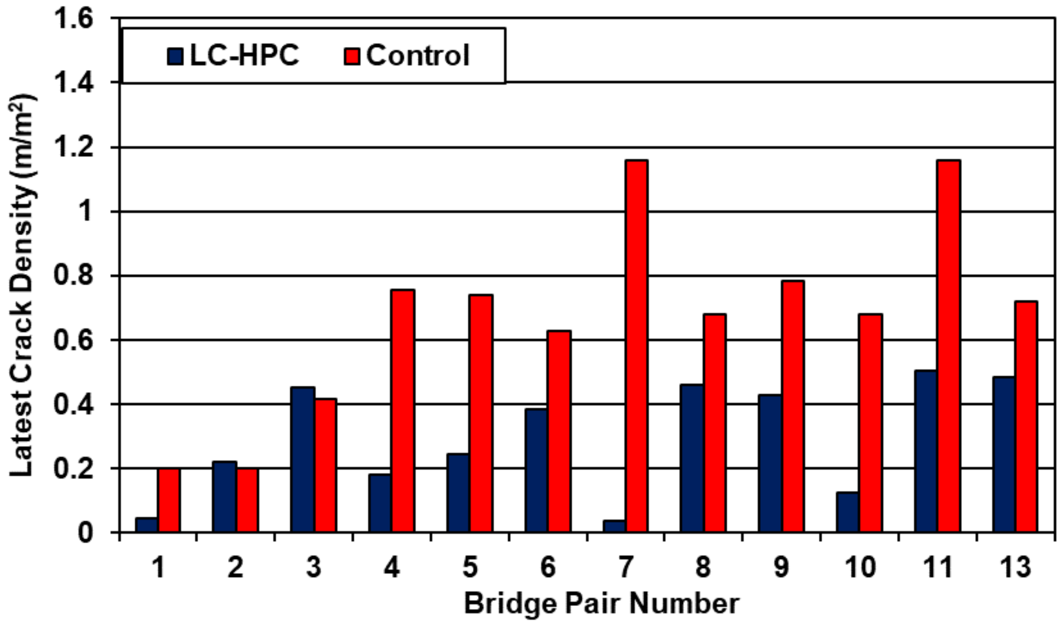

Fig. 5—Comparison of Crack Density between each LC-HPC and its Control pair*
** LC-HPC-12 and Control-12 are not shown*

Starting in the summer of 2015, crack widths were measured for most of the bridges that were surveyed. Crack widths were measured using a wallet-sized crack comparator. The accuracy of the comparator was verified with multiple devices. Results of more than 500 cracks width measurements indicate that most of the crack widths for cracks that can be seen from waist height have widths between 0.006 and 0.025 in. (0.150 mm to 0.635 mm).

SUMMARY AND CONCLUSIONS

Low-Cracking High-Performance Concrete (LC-HPC) specifications have been developed by KDOT and the University of Kansas for the purpose of increasing the expected service life of concrete bridge decks by the reduction of cracking. Surveys of LC-HPC and control bridge decks were performed and crack densities compared to examine the benefits of implementing LC-HPC specifications. Comparisons between 13 LC-HPC and matching control bridge decks are made based on the crack density and changes in crack density over time.

Based on the results of this study, the following conclusions can be drawn:

1. The LC-HPC bridge decks exhibit less cracking than the matching control decks in the vast majority of cases.
2. Most of the cracks observed on the bridge decks in this study were transverse cracks. Cracks of this type appear to run directly over and parallel to the top layer of reinforcement in the decks.
3. Near the abutments, cracks usually propagate perpendicular to the abutments.
4. The widths of the cracks generally range from 0.006 to 0.025 in. (0.15 to 0.64 mm).
5. Reduced cementitious material and cement paste contents, improved early-age and long-term curing, limitations on or de-emphasis of maximum concrete compressive strength, limitations on maximum slump, concrete temperature control, and minimizing finishing operations help minimize cracking in bridge decks.
6. High-slump concrete, poor consolidation, delayed curing, and over-finishing result in increased cracking in bridge decks.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Kansas Department of Transportation (KDOT) serving as the lead agency for the "Construction of Crack-Free Bridge Decks, Phase II" Transportation Pooled Fund Study, Project No. TPF-5(174). The Colorado DOT, Idaho Transportation Department, Indiana DOT, Michigan DOT, Minnesota DOT, Mississippi DOT, New Hampshire DOT, New York DOT, North Dakota DOT, Ohio DOT, Oklahoma DOT, Texas DOT, Wisconsin DOT, the University of Kansas Transportation Research Institute, BASF Construction

Chemicals, and the Silica Fume Association provided funding to the pooled fund. Representatives from each sponsor served on a Technical Advisory Committee that provided advice and oversight to the project. Thanks are also due to the KDOT personnel who provided support, guidance, and construction supervision, the contractors, material suppliers, and subcontractors who worked on the bridges, and the sponsors of the first phase of "Construction of Crack-Free Bridge Decks" Transportation Pooled Fund Study, Project No. TPF-5(051), including Kansas Department of Transportation serving as the lead agency, the Federal Highway Administration (FHWA) of the U.S. Department of Transportation (DOT), Delaware DOT, Idaho Transportation Department, Indiana DOT, Michigan DOT, Minnesota DOT, Mississippi DOT, Missouri DOT, Montana DOT, New Hampshire DOT, North Dakota DOT, Oklahoma DOT, South Dakota DOT, Texas DOT, Wyoming DOT, Overland Park, KS, and the University of Kansas Transportation Research Institute. LRM Industries, BASF Construction Chemicals, Holcim US, Fordyce Concrete, Grace Construction Products, Ash Grove Cement, and Lafarge North America provided concrete materials for laboratory studies. Last, but certainly not least, it is important to acknowledge the contributions of Dr. JoAnn Browning, Dean of Engineering at the University of Texas at San Antonio (UTSA), who served at the Co-Principal Investigator of this project prior to joining UTSA, and the earlier graduate students who contributed to the project: Drs. Will Lindquist, Heather McLeod, Jiqiu Yuan, Ben Pendergrass, and Miriam Toledo, and Diane Reynolds, Dan Gruman, Maria West, Nathan Tritsch, Swapnil Deshpande, Amber Harley, Vinur Kaul, Jeff Peckover, Pankaj Shrestha, Brent Bohaty, Elizabeth Riedel, Grant Polley, Osama Al-Qassag, and Ryan Brettmann.

REFERENCES

Alhmood, A.; Darwin, D.; and O'Reilly, M., 2015, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas 2014-2015," *SL Report* 15-3, University of Kansas Center for Research, Lawrence, KS, Sep., 118 pp.

ASCE, 2017, "2017 Infrastructure Report Card," American Society of Civil Engineers. <https://www.infrastructurereportcard.org/cat-item/bridges/>

Bohaty, B.; Riedel, E.; and Darwin, D., 2013, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas 2011-2013," *SL Report* 13-6, University of Kansas Center for Research, Lawrence, KS, Dec., 153 pp.

Browning, J.; Darwin, D.; and Hurst, K., 2007, "Specifications to Reduce Bridge Deck Cracking," *HPC Bridge Views*, Issue No. 46, Sep./Oct., pp. 1-2.

Browning, J.; Darwin, D.; and Hurst, K., 2009, "Specifications to Reduce Bridge Deck Cracking," *HPC Bridge Views*, Issue No. 55, May/June, pp. 1-3.

Darwin, D.; Browning, J.; and Lindquist, W. D., 2004, "Control of Cracking in Bridge Decks: Observations from the Field," *Cement, Concrete and Aggregates*, ASTM International, V. 26, No. 2, Dec. pp. 148-154.

Darwin, D.; Browning, J.; Lindquist, W.; McLeod, H. A. K.; Yuan, J.; Toledo, M.; and Reynolds, D., 2010, "Low-Cracking, High-Performance Concrete Bridge Decks – Case Studies Over the First 6 Years," *Transportation Research Record: Journal of the Transportation Research Board*, No. 2202, pp. 61-69.

Darwin, D.; Khajehdehi, R.; Alhmood, A.; Feng, M.; Lafikes, J.; Ibrahim, K.; and O'Reilly. M., 2016, "Construction of Crack-Free Bridge Decks: Final Report," *SM Report* No. 121, University of Kansas Center for Research, Lawrence, KS, Dec., 160 pp.

Darwin, D.; Browning, J.; McLeod, H. A. K.; Lindquist, W.; and Yuan, J., 2012, "Implementing Lessons Learned From Twenty Years of Bridge-Deck Crack Surveys," *Andy Scanlon Symposium on Serviceability and Safety of Concrete Structures: From Research to Practice*, SP-284, American Concrete Institute, Farmington Hills, MI, pp. 8-1–8-17~~.~~

Darwin, D., 2014, "Low-Cracking High-Performance Bridge Decks," *Concrete Bridge Views*, Issue No. 78, September/October. http://www.concretebridgeviews.com/i78/Article2.php

Gruman, D.; Darwin, D.; and Browning, J., 2009, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas 2006-2008," *SL Report* 09-1, University of Kansas Center for Research, Lawrence, KS, Jan., 50 pp.

Kansas Department of Transportation, 2007a, "Low-Cracking High-Performance Concrete - Aggregates," Standard Specifications for State Road and Bridge Construction, Topeka, KS.

Kansas Department of Transportation, 2007b, "Low-Cracking High-Performance Concrete," Standard Specifications for State Road and Bridge Construction, Topeka, KS.

Kansas Department of Transportation, 2007c, "Low-Cracking High-Performance Concrete - Construction," Standard Specifications for State Road and Bridge Construction, Topeka, KS.

Kaul, V., Darwin, D., and Browning, J., 2012, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas 2010-2011," *SL Report* 12-4, University of Kansas Center for Research, Lawrence, KS, Dec., 77 pp.

Lindquist, W.; Darwin, D.; and Browning, J., 2005, "Cracking and Chloride Contents in Reinforced Concrete Bridge Decks," *SM Report* No. 78, University of Kansas Center for Research, Lawrence, KS, Feb., 453 pp.

Lindquist, W.; Darwin, D.; Browning, J.; and Miller, G. G., 2006, "Effect of Cracking on Chloride Content in Concrete Bridge Decks," *ACI Materials Journa*l, V. 103, No. 6, Nov.-Dec., pp. 467-473.

Lindquist, W. D.; Darwin, D.; and Browning, J. P., 2008, "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture Optimization, and Concrete Production" *SM Report* No. 92, University of Kansas Center for Research, Lawrence, KS, Nov., 540 pp.

Lindquist, W.; Darwin, D.; Browning, J.; McLeod, H. A. K.; Yuan, J.; and Reynolds, D., 2015, "Implementation of Concrete Aggregate Optimization," *Construction & Building Materials*, V. 74, Jan., pp. 49-56.

McLeod, H. A. K.; Darwin, D.; and Browning, J., 2009, "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Construction Methods, Specifications, and Resistance to Chloride Ion Penetration," *SM Report* No. 94, University of Kansas Center for Research, Lawrence, KS, Sep., 815 pp.

Pendergrass, B.; Darwin, D.; and Browning, J., 2011, "Crack Surveys of Low-Cracking High-Performance Concrete Bridge Decks in Kansas 2009-2010," *SL Report* 11-3, University of Kansas Center for Research, Lawrence, KS, Oct., 103 pp.

Pendergrass, B.; Shrestha, P.; Riedel, E.; Polley, G.; and Darwin, D., 2013, "Evaluation of Cracking Performance of Bridge Decks in Minnesota," *SL Report* 13-4, University of Kansas Center for Research, Lawrence, KS, Oct., 24 pp.

Pendergrass, B., and Darwin, D., 2014, "Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Shrinkage-Reducing Admixtures, Internal Curing, and Cracking Performance," *SM Report* No. 107, The University of Kansas Center for Research, Lawrence, KS, Jan., 664 pp.

Schmitt, T. R., and Darwin, D., 1995, "Cracking in Concrete Bridge Decks," *SM Report* No. 39, University of Kansas Center for Research, Lawrence, KS, Apr., 151 pp.

Schmitt, T. R. and Darwin, D., 1999, "Effect of Material Properties on Cracking in Bridge Decks," *Journal of Bridge Engineering*, ASCE, V. 4, No. 1, Feb., pp. 8-13.

Shilstone, J. M., Sr., 1990, "Concrete Mixture Optimization," *Concrete International*, V. 12, No. 6, June, pp. 33-39.

Yuan, J.; Darwin, D.; and Browning, J., 2011, "Development and Construction of Low-Cracking High-Performance Concrete Bridge Decks: Free Shrinkage Tests, Restrained Shrinkage Tests, Construction Experience, and Crack Survey Results," *SM Report* No. 103, University of Kansas Center for Research, Lawrence, KS, Sep., 505 pp.

AUTHOR BIOS

ACI Honorary Member **David Darwin** is the Deane E. Ackers Distinguished Professor and Chair of the Department of Civil, Environmental, and Architectural Engineering at the University of Kansas and a Past President of ACI.

ACI member **Rouzbeh Khajehdehi**, is a Graduate Research Assistant at the University of Kansas. He received his MS in civil engineering from the Southern Illinois University, Edwardsville, IL.

ACI member **Muzai Feng,** is a Graduate Research Assistant at the University of Kansas. He received his MS in civil engineering from the University of Kansas, Lawrence, KS.

ACI member **James Lafikes** is a Graduate Research Assistant at the University of Kansas. He received his MS in civil engineering from the University of Kansas, Lawrence, KS.

ACI member **Eman Ibrahim**, is a Graduate Research Assistant at the University of Kansas. She received her MS in civil engineering from the Mosul University, Mosul, Iraq.

ACI member **Matthew O'Reilly,** is an Assistant Professor at the University of Kansas. He received his Ph.D. in civil engineering from the University of Kansas, Lawrence, KS.

APPENDIX A—CRACK DENSITY COMPARISONS

Table A.1—2014 Crack Density Comparisons of LC-HPC vs. Control decks

Bridge Name	Bridge Location	Deck Age (months)	2014 Crack Density (m/m^2)	Bridge Girder Type
LC-HPC-1	EB Parallel Pkwy over I-635	102.5/103.1[Y]	0.043/0.024[Y]	Steel
Control-1/2	WB Parallel Pkwy over I-635	103.3/102.7	0.106/0.217	
LC-HPC-2	34th St. over I-635	92.2	0.116	Steel
Control-1/2	WB Parallel Pkwy over I-635	103.3/102.7	0.106/0.217	
LC-HPC-3	WB 103rd over US-69	79.4	0.759	Steel
Control-3	EB 103rd St. over US-69	83.2	0.376	
LC-HPC-4	SB US-69 to I-435 Rp over 103rd St	80.4/80.3	0.371/0.173	Steel
Control-4	Antioch to WB I-435 & NB US-69/Rp/WB I-435 to NB US-69 Rp	80.7	0.667	
LC-HPC-5	SB US-69 to WB I-435 Rp over Quivera Rp	79.4	0.229	Steel
Control-5*	SB US-69 to EB I-435 Rp over US-69 Hwy and I-435	30.6	0.738	
LC-HPC-6	SB US-69 to WB I-435 Rp over WB I-435 to Quivera Rp	79.7	0.356	Steel
Control-6	SB US-69 to EB I-435 Rp over US-69 Hwy and I-435	68.2	0.646	
LC-HPC-7	Co Rd 150 over US-75	95.7	0.087	Steel
Control-7	NB Antioch over I-435	74.5/68.9	1.022/0.638	
LC-HPC-8	E 1350 Rd over US-69	81.6	0.425	Precast Prestressed Concrete
Control-8/10	K-52 over US-69	87.2	0.566	
LC-HPC-9	NB US-69 over Marais Des Cygnes River	62	0.454	Steel
Control-9	SB US-69 over Marais Des Cygnes River	73.8/74.1	0.733	
LC-HPC-10	E 1800 Rd over US-69	86.2	0.117	Prestressed Concrete
Control-8/10	K-52 over US-69	87.2	0.566	
LC-HPC-11	EB US-50 over K&O RR	84.8	0.842	Steel
Control-11	US-50 over BNSF RR	98	0.922	
LC-HPC-12	Unit 2 K-130 over Neosho River	64.9/76.3	0.657	Steel
Control-12	Unit 1 K-130 over Neosho River	64.0/76.4	1.152	
LC-HPC-13	NB US-69 over BNSF RR	75.2	0.471	Steel
Control-13	SB US-69 over BNSF RR	72.5	0.711	
LC-HPC-15	NB K-7 over Johnson Dr./55th St	43	0.317	Steel
LC-HPC-16	SB K-7 over Johnson Dr./55th St	43.5	0.311	Steel
LC-HPC-17	Clear Creek Parkway over K-7	32.5	0.274	Steel

[Y] Slash separates age and density for different placements; * 2011

Table A.2—2015 Crack Density Comparisons of LC-HPC vs. Control decks

Bridge Name	Bridge Location	Deck Age (months)	2015 Crack Density (m/m^2)	Bridge Girder Type
LC-HPC-1	EB Parallel Pkwy over I-635	15.1/114.5	0.045	Steel
Control-1/2	WB Parallel Pkwy over I-635	115.6/115.3	0.189	
LC-HPC-2	34th St. over I-635	104.2	0.222	Steel
Control-1/2	WB Parallel Pkwy over I-635	115.6/115.3	0.189	
LC-HPC-3	WB 103rd over US-69	91.5	0.487	Steel
Control-3	EB 103rd St. over US-69	96.9	0.391	
LC-HPC-4	SB US-69 to I-435 Rp over 103rd St	93.3/93.2	0.217	Steel
Control-4	Antioch to WB I-435 & NB US-69/Rp/WB I-435 to NB US-69 Rp	92.9	0.775	
LC-HPC-5	SB US-69 to WB I-435 Rp over Quivera Rp	91.8	0.247	Steel
Control-5*	SB US-69 to EB I-435 Rp over US-69 Hwy and I-435	30.6	0.738	
LC-HPC-6	SB US-69 to WB I-435 Rp over WB I-435 to Quivera Rp	92.2	0.386	Steel
Control-6	SB US-69 to EB I-435 Rp over US-69 Hwy and I-435	81.9	0.628	
LC-HPC-7	Co Rd 150 over US-75	106.9	0.036	Steel
Control-7[#]	NB Antioch over I-435	74.5/68.9	1.022/0.638	
LC-HPC-8	E 1350 Rd over US-69	92.0	0.462	Precast Prestressed Concrete
Control-8/10	K-52 over US-69	98.1	0.680	
LC-HPC-9	NB US-69 over Marais Des Cygnes River	73.6	0.430	Steel
Control-9	SB US-69 over Marais Des Cygnes River	84.4/84.1	0.779	
LC-HPC-10	E 1800 Rd over US-69	96.8	0.125	Prestressed Concrete
Control-8/10	K-52 over US-69	98.1	0.680	
LC-HPC-11[#]	EB US-50 over K&O RR	84.8	0.842	Steel
Control-11[#]	US-50 over BNSF RR	98	0.922	
LC-HPC-12[#]	Unit 2 K-130 over Neosho River	64.9/76.3	0.657	Steel
Control-12[#]	Unit 1 K-130 over Neosho River	64.0/76.4	1.15*	
LC-HPC-13	NB US-69 over BNSF RR	85.9	0.486	Steel
Control-13	SB US-69 over BNSF RR	84.1	0.718	
LC-HPC-15	NB K-7 over Johnson Dr./55th St	56.2	0.299	Steel
LC-HPC-16	SB K-7 over Johnson Dr./55th St	55.0	0.397	Steel
LC-HPC-17	Clear Creek Parkway over K-7	45.5	0.308	Steel

[Y] Slash separates age and density for different placements; * 2011; [#] 2014

Table A.3—2016 and 2017 Crack Density Comparisons of LC-HPC vs. Control decks

Bridge Name	**Bridge Location**	**Deck Age (months)**	**2016 Crack Density (m/m²)**	**Bridge Girder Type**
LC-HPC-3	WB 103rd over US-69	105	0.453	Steel
Control-3	EB 103rd St. over US-69	115.3	0.416	
LC-HPC-11	EB US-50 over K&O RR	110.7	0.883	Steel
Control-11	US-50 over BNSF RR	124.9	1.16	
			2017 Crack Density (m/m²)	
LC-HPC-15	NB K-7 over Johnson Dr./55th St	78.2	0.293	Steel
LC-HPC-16	SB K-7 over Johnson Dr./55th St	78	0.356	Steel
LC-HPC-17	Clear Creek Parkway over K-7	67.9	0.327	Steel